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Invited Paper

NPOI: recent technology and science

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ABSTRACT

We describe recent science projects that the Navy Prototype Optical Interferometer (NPOI) scientific staff and collaborators are pursuing. Recent results from the wide angle astrometric program and imaging programs (rapid rotators, binaries and Be stars) will be summarized. We discuss some of the technology that enables the NPOI to operate routinely as an observatory astronomical instrument.

Keywords: Optical interferometry, astrometry, imaging, NPOI

1. INTRODUCTION

In this paper we give an overview of progress on the NPOI since the Waikoloa SPIE 2002 meeting. We also discuss some recent science projects utilizing the NPOI that are being pursued by NPOI scientific staff and collaborators. Some of the recent technological upgrades to the NPOI are also discussed.

2. ASTROMETRY: TECHNOLOGY AND SCIENCE

As has been discussed in the literature, e.g. Armstrong et al.,[1] the NPOI was originally designed to operate in either an imaging mode or an astrometric mode. A recent upgrade specific to the astrometric mode has been the addition of a nearly end-to-end internal path length metrology system. Historically the internal instrument delay term has been designated by the misnomer *constant term* (CT). Of course, at the micron level, the internal instrument delay is anything **but** constant. With the addition of our internal path length metrology system (CT metrology) we can now monitor this delay during on sky astrometric observations. The CT-metrology measured-changes in the internal instrument delay are then used in the astrometric data reductions to correct for internal path length changes.

The CT metrology beams are injected into the feed beam system from the temperature-stable beam combining room. Figure 1 shows the injection optics. Once the CT beams are in the feed system, they travel in reverse along the star light path until they reach a small cube corner reflector that is placed as near to the siderostat mirror as possible. Figure 2 shows the CT cube corner in the astrometric west hut. The CT cube corner is positioned in the shadow of the siderostat metrology cat's-eye. Except for the thin strut holding the CT cube corner no additional star light is occulted. The CT cube corner then reflects the CT beam back along the star light path until the CT injection optics retrieve the return beam, where it is combined with the stable reference arm of the metrology interferometer and then sent on to the CT detector.

In order to minimize the cost and need for specialized electronics for the CT metrology system, we utilized a standard PC and an off-the-shelf ADC. The PC runs real-time Linux (`http://www.aero.polimi.it/~rtai`) and directly digitizes the reference and measurement analog sinusoidal signals of the metrology interferometer. The necessary phase detection and fringe counting is all done in software. Additional cost saving was achieved by digitizing the analog Inter Range Instrumentation Group (IRIG) timing signal that we pipe around the site for timing synchronizations. The decoding of the digitized IRIG signal is also done in software. This decoding

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14. ABSTRACT
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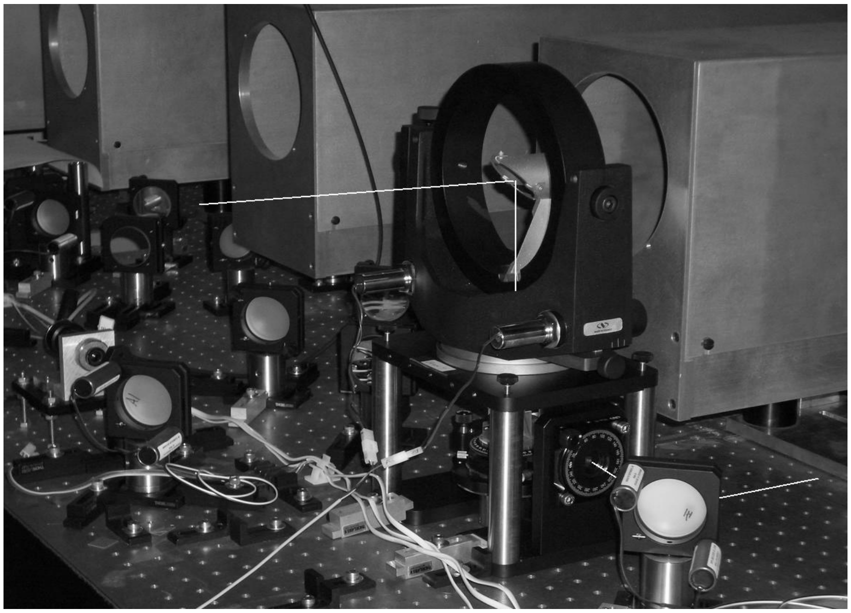

Figure 1. CT metrology injection optics. The dotted white line starting at the lower right indicates the path of the injected metrology beam.

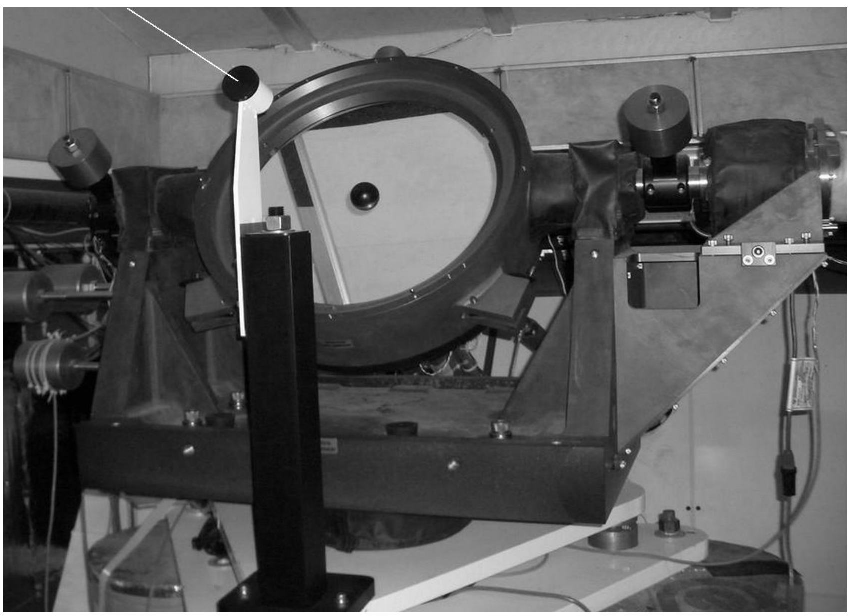

Figure 2. CT metrology cube corner at the siderostat. The dotted white line starting at the upper left indicates the path of the metrology beam.

and time tagging serves to precisely synchronize the CT metrology data with the same IRIG signal that is used to time tag the stellar fringe data and fast delay line metrology data.

The CT metrology recorder runs continuously during an astrometry night. In addition to continuously recording the CT data, we also position the siderostats in retro-reflection mode and record fringes from a lab source (congenially known as Alp Lab) periodically throughout the night. The Alp Lab measurements are used

to correct for the fact that the CT cube corner is not directly on the surface of the siderostat. Figure 3 shows an example of the differential CT data after they have been calibrated to the Alp Lab measurements. It is readily

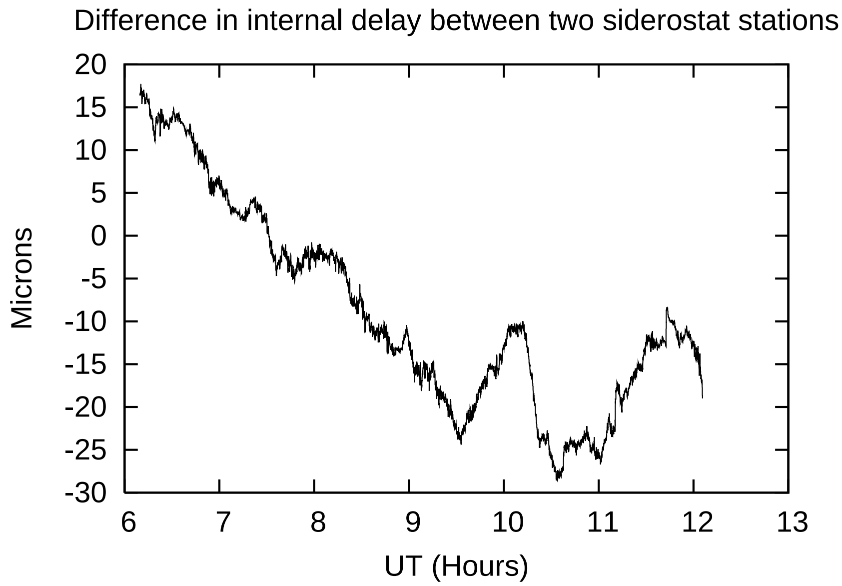

Figure 3. The difference in delay between two siderostat stations as measured by the CT metrology system.

apparent from Fig. 3 that a simple linear, or low-order polynomial, interpolation between Alp Lab measurements, typically obtained every 45 minutes, would in general give a poor representation of the actual internal delay variations for arbitrary times. Figure 4 shows fringe delay atmospheric dispersion corrected residuals on Polaris before correcting by the CT metrology measurements of the internal delay shown in Fig. 3. Figure 5 shows the fringe delay atmospheric dispersion corrected residuals after applying the internal delay correction shown in Fig. 3. The RMS of the residuals in Fig. 5 is 1.5 microns. The rule of thumb for converting such delay residuals to astrometric precision is 10 milliarcseconds/micron.

3. IMAGING: TECHNOLOGY AND SCIENCE

Since the SPIE 2002 meeting, we have not done any hardware upgrades that are specific to the imaging operational mode of the NPOI. A number of the technological details of the NPOI imaging operations were discussed by Benson et al.[2] in the Proceedings of the 2002 conference.

New techniques have been developed, see Clark et al.,[3] for initially aligning the internal mirrors in the *elevator* vacuum cans that are placed at every potential siderostat station on the array.

We have made significant advances in automating some of the NPOI optical alignment tasks. See the following Sect. 4 for a description of these upgrades.

A number of NPOI imaging science projects have come to fruition since the 2002 conference. Here we give a short introduction to the papers in these Proceedings that describe these results in detail.

3.1. RAPID ROTATORS

Peterson et al.[4] report on observations obtained with the NPOI of the bright A stars, Vega and Altair. The authors report on the detection of significant asymmetries in the brightness distributions of both stars. Both brightness distributions are well modeled by simple Roche spheroids including gravity darkening, as expected for rapidly rotating stars. In the case of Vega, the model suggests that the star is near breakup and is sharp lined because it is seen nearly pole on.

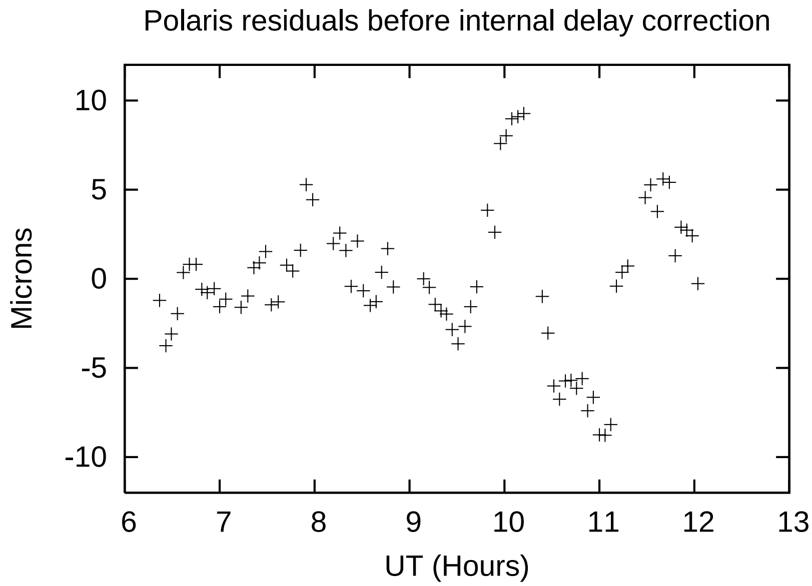

Figure 4. Atmospheric dispersion corrected fringe delay residuals before applying the internal delay correction as measured by the CT metrology.

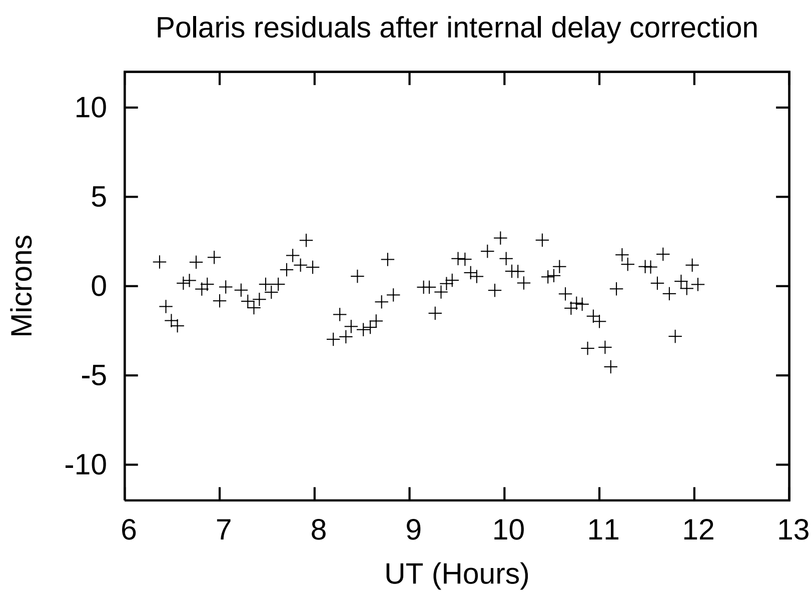

Figure 5. atmospheric dispersion corrected fringe delay residuals after applying the internal delay correction as measured by the CT metrology.

On a similar topic, Hummel et al.[5] report on applying improved data analysis techniques to observations of Altair obtained with the NPOI. The authors find general agreement with the oblateness of Altair as discovered by van Belle et al.[6] with the Palomar Testbed Interferometer.

3.2. BINARY STARS

Hutter et al.[7] report on observations using the NPOI to support the Terrestrial Planet Finder (TPF) mission. Here the authors report on the use of the NPOI to help cull down the list of target stars for the TPF mission. To date, 29 of the 60 brightest (V $\leq$ 4.3) candidate stars north of Dec = -20 deg have each been observed on multiple nights. Preliminary analysis of these data indicate the possible detection of stellar companions to several of these stars.

Armstrong et al.[8] report on using precisely scheduled observations with the NPOI to observe binaries. The times of the observations are carefully chosen to correspond with the time that a projected baseline is perpendicular to the expected position angle of the binary. The authors show that very precise astrometric parameters of the binary can be obtained from such observations.

3.3. HYDROGEN ALPHA IMAGING

Gilbreath et al.[9] report on NPOI closure phase observations obtained in and out of the H-alpha line on a number of Be stars.

Tycner et al.[10,11] have used the unique multichannel spectral capabilities of the NPOI to measure the size and orientation of the emission line regions around Be stars. The authors use a technique that can be considered a form of self-calibration in which the spectral channels in the continuum are used to calibrate the channel where the H-alpha line occurs. Briefly, the technique is to fit a quadratic polynomial to the channels that lie outside the line and apply the result to the line data. The authors apply the technique to the stars γ Cassiopeia and ζ Tauri. See their papers[10,11] for the complete details.

4. TECHNOLOGY AND AUTOMATED ALIGNMENT

The NPOI, like any other optical or infrared interferometer, has *a lot* of mirrors. The alignment of a subset of these mirrors must be checked and possibly adjusted every night prior to observing. It has always been our goal to automate this alignment process as much as possible (see White et al.[12] for a recent discussion of the benefits of such automation). As such, we have recently outfitted all of our mirrors on our optical switch yard table (beam relay table between the fast delay lines and the beam combiner table) with motorized micrometers. We have a manual *paddle* controller that can be plugged into any of the motorized micrometers via telephone cable patch panels. The manual controller enables pulse and slew control of the motorized micrometers. In addition, the motorized micrometers are also wired into controllers that can be addressed by a computer over a serial link. The computer controllers enable computerized pulse control of the motors. The controllers also have various bit I/O lines for control of DC motors and digital status information. In addition to control of the relevant mirrors, an automatic alignment requires feedback on how the alignment is proceeding. We are using large area quad cells (LAQs) to provide this feedback. The LAQ design considerations and engineering tests on prototype cells was discussed in Gilbreath and Mozurkewich.[13] We have now built controllers and motorized mounts for these LAQs and installed the quad cells on the switch yard table. A close up of a beam's motorized mirrors and LAQ as installed on the optical switch yard table is shown in Fig. 6. Here the LAQ is shown in the upper active alignment position. The other alignment position is when the beam's LAQ is flipped down and it intercepts the lower beam before the fast delay line. Figure 7 shows the LAQ in the lower alignment position. A stow sensor is also provided so that the computer can position the LAQ at a position between the two vertical beams so that star light can pass over and below the stowed LAQ. This stowed orientation is shown in Fig. 8.

We have demonstrated automated closed loop alignments of the switch yard table mirror LAQ combinations on all six beams. We are currently working on making the auto alignment servo faster and more robust.

5. CONCLUSIONS

With the recent addition of an internal delay metrology system, we have shown that the NPOI is now technologically capable of making astrometric observations with a nightly precision approaching 15 milliarcseconds.

Another technological milestone towards automation of the nightly alignments of various beam relay mirrors has been reached with the installment and near complete implementation of the LAQ alignment system.

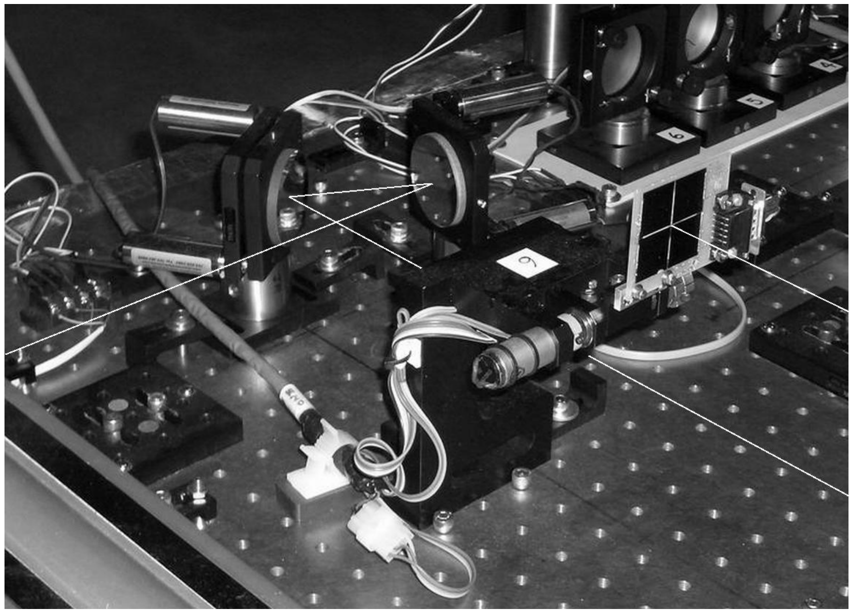

Figure 6. Motorized mirrors and large area quad cell in the upper alignment position. The dotted white line starting at the left indicates the path of the alignment metrology beam. The alignment beams goes off to the lower right towards the fast delay line. After traversing the fast delay line cart optics, the beam returns, offset in a vertical plane, and impinges on the large area quad cell.

The ever increasing automation of the NPOI and subsequent ease of operation continues to improve its observing efficiency. This enables the NPOI scientific staff and collaborators to pursue a number of science programs with the NPOI. Discussions of a number of these programs are presented elsewhere in the Proceedings of this conference (see Sect. 3 for explicit references).

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Figure 7. Large area quad cell in the lower alignment position.

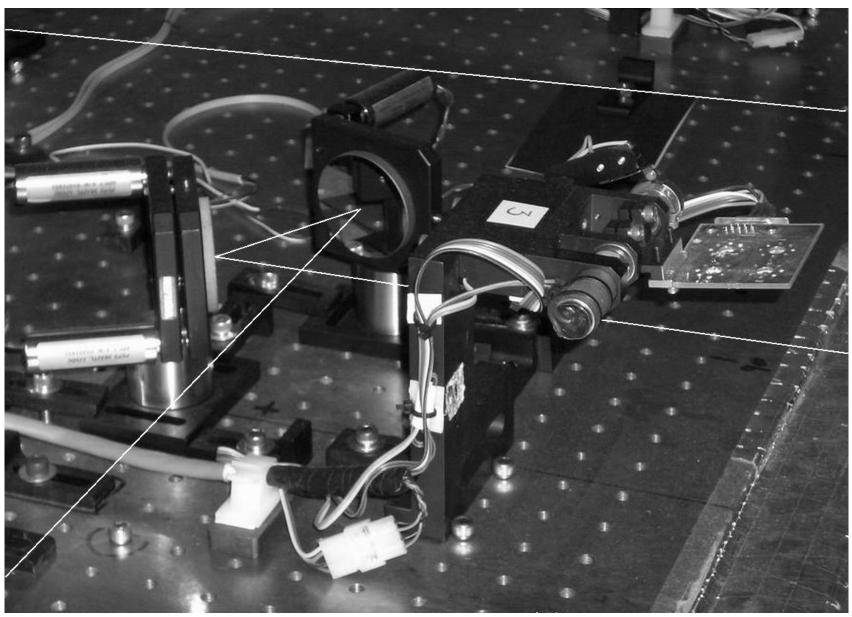

Figure 8. Large area quad cell in the stow position. The starlight beam passes over the top of the LAQ, through the fast delay line, returns offset in the vertical plan, passes under the LAQ and then on to the beam combining table.

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